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14. ABSTRACT

When some elastomer (rubber) compounds, and specifically those used for seals in fuel-wetted components of vehicles and equipment, are suddenly "switch-loaded" from a fuel of given composition to one of a somewhat different composition, swell/shrink issues relating to seal performance may arise, possibly leading to fuel leakage. The key objective of this study was to evaluate what happens to the elastomers with sudden switches from a conventional (petroleum-derived) fuel to a synthetic (non-aromatic) paraffinic fuel produced from natural gas using gas-to-liquids (GTL) and Fischer-Tropsch (FT) synthesis processes with or without surrogate aromatics. Results from this evaluation indicate that, for the nitrile elastomers evaluated, relatively large swings in swell occur with switches between fuels of varying levels of aromatic content and the synthetic aviation turbine fuel containing no aromatics. These observations support the conclusion that impact on the nitrile elastomer when switch-loading synthetic (non-aromatic) and petroleum-derived fuel, is highly dependent on aromatic hydrocarbon type and concentration.

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– TECHNICAL REPORT –

No. 16028

ELASTOMER IMPACT WHEN SWITCH-LOADING SYNTHETIC FUEL BLENDS AND PETROLEUM FUELS

July 2006

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THE NATION'S LABORATORY FOR ADVANCED AUTOMOTIVE TECHNOLOGY

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Development, and Engineering Center
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ELASTOMER IMPACT WHEN SWITCH-LOADING SYNTHETIC FUEL BLENDS AND PETROLEUM FUELS

FINAL REPORT

Note: This report approved for public release and under provision of the DoD-DoE MOA for collaborative research and development in the assessment of alternative fuels, particularly synthetic JP-8/JP-5 produced from Fischer-Tropsch technology, and Contract DAAE07-02-C-L070 associated with the Flexible JP-8 Pilot Plant Program.

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National Automotive Center,
Alternative Fuels and Fuel Cell Technology Team
and
Petroleum & Water Business Area,
Fuels and Lubricants Technology Team
and the
Warren, MI

July 2006

EXECUTIVE SUMMARY

Problems and Objectives

Issues with seal performance may arise and possibly lead to fuel leakage when some elastomer (rubber) compounds, particularly those used for seals in liquid fuel-wetted components of vehicles and equipment, are suddenly “switch-loaded” from one kind of fuel to another. Evaluating how these elastomers respond as they are switched back-and-forth between two fuels of different compositions is a key area of study. This type of study is needed to identify potential performance issues that may arise when such fuel switches occur. The overall objective of this study was to simulate how elastomers, found in fuel-wetted components of Army ground and combat vehicles, may respond when switching fuels. In particular, this study evaluates what happens to the elastomers with sudden switches from a conventional or petroleum-derived type of fuel to a synthetic (non aromatic) paraffinic fuel produced from natural gas using gas-to-liquids (GTL) and Fischer-Tropsch (F-T) synthesis processes with or without surrogate aromatics. Studies conducted in 2003 indicate that nitrile elastomers may be particularly sensitive to changes as they are exposed to fuels and that the magnitude and direction of these changes is also dependent on the aromatic content of the fuel.

Importance of Project

This study was completed under a joint DoD-DoE Memorandum of Agreement (MOA) to conduct collaborative research and development in the assessment of alternative fuels, particularly synthetic military fuel produced from GTL and F-T technology. This project is one of several second year efforts under this MOA to address the potential use of F-T fuels by the military.

Technical Approach

To assess the response of selected elastomers to switches between fuel pairs, coupons and O-rings of the selected elastomer were immersed in the first fuel of each fuel pair and remained there, at 40°C temperature, for a period of 43 days. At that point, the coupons and O-rings were then switched into the second fuel of each fuel pair, also at the same elevated temperature, and held there long enough to reach equilibrium before being switched back into the first fuel again. This switching cycle was repeated several times. Prior to immersion, and then at several intervals thereafter, measurements were made to determine net changes in coupon mass, volume, and hardness. For O-rings, measurements were made to determine net changes in inner diameter and cross-sectional diameter as well.

Accomplishments

Results from this evaluation indicate that for the nitrile elastomer evaluated, relatively large swings in swell occurred with switches between fuels of varying levels of aromatic content and the synthetic aviation turbine fuel containing no aromatics. Comparisons in swell swings were particularly noted for two surrogate aromatic-synthetic fuel blends. It was concluded that elastomer impact when switch-loading (non-aromatic) synthetic and petroleum-derived fuel is highly dependent on aromatic hydrocarbon type and concentration.

Military Impact

As the U.S. Military considers fuel sources around the world and into the future, it may very well someday happen that fuels produced via non-conventional means become increasingly available and of growing importance. One such type of fuel, a synthetic fuel, can today be produced from a synthesis process first developed in the 1920’s known as Fischer-Tropsch. As a matter of fact, some limited production of coal-derived synthetic fuel has been a reality since the early 1970’s in South Africa, and starting in the early 1990’s synthetic fuel derived from natural gas has been produced in Bintulu, Indonesia. The possibility for the use of synthetic fuels by the U.S. Military opens up a whole new dimension in considering sources of supply. In turn, various scenarios for the production of synthetic fuel can be envisioned which could significantly increase energy security and enhance mobility for the U.S. Military. Development of military specifications for fuel made from petroleum, as well as synthetic hydrocarbons, relies on military material evaluation data such as the elastomeric materials evaluations provided in this report.

FOREWARD/ACKNOWLEDGMENTS

This work was performed during FY04 at the labs of the Petroleum and Water Business Area (PWBA), part of the Tank-Automotive Research Development and Engineering Center (TARDEC) of the U.S. Army Research, Development and Engineering Command (RDECOM) located in Warren, MI. The funding for this work was provided through a FY04 Congressional Plus-up to study the concept of a barge-mounted plant for the production of synthetic JP-8/JP-5 fuel. This funding was allocated through the Office of the Secretary of Defense (OSD), Dr. Theodore K. Barna, Assistant Deputy-Undersecretary of Defense/Advanced Systems and Concepts to the National Automotive Center (NAC), responsible for overall program management.

The authors would like to acknowledge the efforts of key contributors to this work. Specifically, to PWBA Fuels & Lubricants Technology Team personnel Kathy Kline and Tonya Tant who performed the various tests involved in this evaluation. We also would like to acknowledge Mr. Herb Dobbs, Team Leader of the Alternative Fuels and Fuel Cell Technology Team, whose efforts in the arena of Fischer-Tropsch fuels for the military over the past few years laid the foundation from which this work arose.

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I. OBJECTIVE

The overall objective of this study was to compare and contrast the response of selected elastomers, some of those typically found in the fuel systems of Army tactical and combat vehicles, when exposed to several fuel pairs that represent an array of fuel hydrocarbon compositional differences. Specifically, the fuel pairs evaluated provided an array of compositional differences allowing characterization of elastomer response as switches occurred from a typical petroleum-derived fuel to a synthetic fuel containing various levels of surrogate aromatics. This testing is intended to simulate how elastomers found in fuel-wetted components of Army ground and combat vehicles , may respond when a sudden switch is made from a conventional or petroleum-derived type of fuel to a synthetic paraffinic fuel produced from natural gas using gas-to-liquids (GTL) and Fischer-Tropsch (F-T) synthesis processes. Data from this study was used to expand on results obtained in prior work.

II. BACKGROUND

With the potential for fuels derived from non-conventional sources, such as from GTL technologies and F-T synthesis, to become increasingly available around the world, their potential use by the U.S. Military needs to be considered. [1][1] As the U.S. Military considers fuel sources around the world and into the future, it may very well someday happen that fuels produced via non-conventional means become increasingly available and of growing importance. One such type of fuel, a synthetic fuel, can today be produced from a synthesis process first developed in the 1920's known as Fischer-Tropsch. As a matter of fact, some limited production of coal-derived synthetic fuel has been a reality since the early 1970's in South Africa, and starting in the early 1990's synthetic fuel derived from natural gas has been produced in Bintulu, Indonesia. The possibility for the use of synthetic fuels by the U.S. Military opens up a whole new dimension in considering sources of supply. In turn, various scenarios for the production of synthetic fuel can be envisioned which could significantly increase energy security and enhance mobility for the U.S. Military.

With this in mind, a joint-agency Memorandum of Agreement (MOA) to study the potential use of these fuels by the military was initiated in late 2002. This MOA, involving Department of Defense (DoD) fuels labs of the Army, Air Force, and Navy, along with the National Energy Technology Laboratory (NETL) of the Department of Energy (DoE), allows for "…cooperative research, development, testing, and evaluation (RDT&E) activities for innovative, alternative, and best-in-kind development and assessment of alternative fuels for the DoD and DoE programs. The principal technology of interest is synthetic JP-8/JP-5 fuel." A synthetic JP-5 like fuel, "S-5", produced by Syntroleum Corporation using their GTL process, was provided as the baseline synthetic fuel for investigation under a FY03 testing program agreed to by DoD and DoE labs.

Elastomeric, or rubber-like, materials are used throughout the fuel distribution systems of air and ground vehicles and equipment as seals, coatings, for hoses and other various applications. These

[1] Numbers between brackets refer to References found at the end of the document.

compounds have varying degrees of resistance and sensitivity to the fuels which they may encounter. Depending on the particular elastomeric type compound (and fillers/plasticizers and curing), some change in dimensions and other properties, such as hardness, may result as the elastomer is exposed to the fuel. These changes do not necessarily result in application performance issues, but may, for instance, when a dramatic change in the type of fuel being used in the vehicle or equipment occurs. It is generally known that aromatic species in hydrocarbon fuels are primary contributors to elastomer swelling. In the case of a seal, aromatic constituents in the fuel will cause seals made from affected elastomers to increase in volume as absorption of the aromatic solute takes place. In likewise fashion, if that seal is then subjected to a fuel containing a much reduced level of aromatic solvents, the process may reverse itself and the seal may then decrease in size (shrink). Such a reduction in the size or volume of the seal at that point in time may result in poor sealing performance and possibly even leakage of fuel. Some aged components may actually exhibit compression set that could allow leakage during shrinkage of a seal (depending on the degree of compression set and other physical considerations). Development of military specifications for fuel that can be made from petroleum, as well as synthetic hydrocarbons, must include performance requirements on military material such as the elastomeric materials evaluations provided in this report.

III. APPROACH

A. Summary of Technical Approach

To assess the response of selected elastomers to switches between fuel pairs, coupons cut from manufactured sheets of the selected elastomer material and O-rings of the same elastomer were immersed in the first fuel of each fuel pair and remained at 40°C temperature for a period of 43 days. At that point, the coupons and O-rings were then switched into the second fuel of each fuel pair, also at the same temperature, and held there long enough to reach equilibrium before being switched back into the first fuel again. This switching cycle was repeated several times. Measurements were made on a larger number of coupons than required by the ASTM methods for determining changes in mass, volume and hardness to enhance the data sets for net changes in these properties. Measurements were also made on a larger number of O-rings than required by the ASTM methods for determining changes in mass and volume. Inner diameter and cross-section diameter of the O-rings were determi ned using optical micrometry.

B. Fuels

The five fuels used in this study are indicated in Table 1. The first fuel listed, designated as “S-5” is a synthetic jet fuel similar to JP-5. [2, 3] This fuel was produced by Syntroleum Corporation using their gas-to-liquids technology to convert natural gas into liquid hydrocarbon fuel. The processes they employ include Fischer-Tropsch synthesis and synthetic crude upgrade to obtain the low freeze point temperature and other properties of JP-5. The fuel properties for the S-5 fuel are shown in Appendix A, Table A-1.

The fourth fuel listing in the table is Emission Control Diesel-1 (ECD-1) from the former Arco Refinery, near Los Angeles, now owned by BP. ECD-1 is a CARB equivalent ultra-low sulfur fuel equivalent[2] No. 2 Diesel, with sulfur < 15 ppm and approximately 19% (wt.) aromatics. [4]

Table 1. Test Fuels

Fuel Name	***Fuel Description***	***Sample ID Number***	***Aromatics by FIA, %V. (ASTM D 1319)***
S-5	0% aromatic content	FL-11741-03	0
S-5 + 10% A150	10% V. aromatic content	FL-11741-03 + 10% FL-11755-03	11
JP-5	18% V. aromatic content	FL-11891-04	18.4
ECD-1	19% V. aromatic content, ultra low sulfur	FL-11749-03	23
S-5 + 25% A150	25% V. aromatic content	FL-11741-03 + 25% FL-11755-03	26
A150	aromatic additive	FL-11755-03	100

As shown in Table 1, the synthetic fuel, S-5, contains no measurable aromatics. This is representative of synthetic fuels that are produced from F-T synthesis utilizing a cobalt-based catalyst and low temperature processes. The other fuels, JP-5 and ECD-1, are representative of aviation kerosene and diesel fuels, respectively, derived from conventional sources, such as petroleum crude oil, in that they contain aromatics. The current specification for low sulfur diesel fuels [5] in the U.S. allows up to 35% (vol.) aromatics. Likewise, the current specification for JP-8 allows up to 25% (vol.) aromatics. [6] JP-8 is the primary battlefield fuel designated for use in all military turbine and diesel engines, except for those used aboard ships, where JP-5 is designated. [7] JP-5 is essentially the same as JP-8, except that JP-5 has a higher minimum flash point that provides added safety for shipboard use.

An aromatic hydrocarbon product manufactured by ExxonMobil, Aromatic 150® (A150), was used as a surrogate for aromatic Jet A-1 for making blends with the S-5. The A150 was added to the S-5 fuel to represent a fully synthetic JP-5/JP-8 fuel containing aromatics at levels, by volume, of 10% and 25%. The two fuel blends created are included in Table 1. Included in Appendix C is the internet link to the datasheets for the aromatic surrogate, Aromatic 150 Fluid. Characterizations of this aromatic surrogate completed by the DoE-National Energy Technology Laboratory are shown Appendix D.

For the purposes of this report, weight percent (% wt) aromatics by ASTM D 5186 (supercrital Fluid Chromatography method used for aromatics) in reference 4, was assumed to be equivalent to volume percent (% V.).

Six fuel pairs were used for switch-loading the elastomers as shown in Table 2. In each case, the elastomer was switch-loaded from either the aromatic-free S-5 fuel or an S-5 blend with A150 to a petroleum fuel (JP-5 or ECD-1), and then back to complete one full switch-loading cycle.

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[2] The term 'fuel equivalent' refers to fuels that meet emission requirements without meeting fuel property requirements.

Aromatic 150 is a trademark of the ExxonMobil Company.

Table 2. Switch-Loading Fuel Pairs

Fuel 1	*Fuel 2*
S-5	JP-5
S-5+**10%** A150	JP-5
S-5+**10%** A150	ECD-1
ECD-1	JP-5
S-5+**25%** A150	JP-5
S-5+**25%** A150	ECD-1

C. Elastomer

Elastomer N0674-70, a general purpose 70-durometer nitrile elastomer, was chosen for this study. Typical properties of this material, compounds of the Parker O-ring Division, are shown in Appendix B, Tables B-1 and B-2. The nitrile was selected for this investigation with the S-5 fuel as it is ". . . representative of today's diesel fuel systems and advanced technology diesel systems." [8] In addition, this elastomer is representative of the types of elastomers found in Army ground and air tactical, and combat fuel systems of the legacy fleet. [9] Finally, this nitrile was evaluated in earlier studies, where it exhibited significant responses to changes in fuel aromatic content. [9-11] Therefore studying the response of nitriles to switch-loading from fuels containing aromatics to one that does not (S-5), or ones that contain synthetic aromatics, is a critical piece of understanding the potential issues that might arise if vehicles and equipment used to being on a "diet" of aromatic-containing fuels suddenly "see" an aromatic-free fuel or a fuel containing surrogate aromatics.

D. Test Procedure

Elastomer coupons, cut from new sheets of the elastomer, and elastomer O-rings were immersed in the first test fuel of the assigned pair. The coupons were cut from elastomer sheets with these dimensions (rectangular) 25 X 50 X 2.0 + 0.1 mm (1 X 2 X 0.008 + 0.004 in.). Four coupons for each fuel were tested and the averages of these measurements were reported. They were stored in the test fuel (230 mL) at 40°C and measurements were taken at 0, 3, 9 and 43 days. The mass change was determined according to ASTM D 471 method. The volume change was determined by the water displacement technique also in the ASTM D 471 method. This time period of 43 days allowed the equilibrium static swell to be achieved. To determine the swelling response, volumetric change due to swell was measured based on a water displacement technique and according to ASTM D 471 procedures. [12] Mass change was also determined according to ASTM D 471. Measurements were made on 4 unique coupons or O-rings for each data point. Hardness measurements were made according to ASTM D 2240 procedures on the coupons. [12] Dimensional measurements for the O-rings were made using an optical microscope with a 10x lens. Four measurements of each dimension were taken at different places on the O-ring. These measurements were then averaged for the reported value.

At the end of the 43 day period in the initial test fuel, the coupons and O-rings were cleaned and dried, measured and then immersed in the second fuel and aged at 40°C. Coupons and O-rings were checked once a week to determine swelling response and measurements were recorded. Once the swelling response was determined to have reached equilibrium, the coupon or O-ring was switched back into the initial fuel for each fuel pair evaluated. The process of making measurements periodically, waiting for equilibrium to be reached, and then switch-loading the elastomer back and forth between the two fuels continued for at least three complete switch-loading cycles.

IV. RESULTS

The results are presented covering the effects of switching loading on the coupons and O-rings using four of the six fuel pairs. The two fuel pairs in which ECD-1 is the second fuel are not presented here for simplicity, but the complete data is represented in Appendix E.

The effects on the nitrile elastomer are shown through changes in the mass, volume, and hardness of the coupons, and through changes in mass, volume, inner diameter and cross section diameter of the O-rings. All of these changes are shown as percent change from original value before being placed in fuel and this value is referred to as the sample in air.

The average mass and volume changes found for Nitrile N0674-70 coupons as switch-loading occurs between S-5 blends and JP-5 are shown in Figures 1 and 2, respectively. The data points represented here are averages determined from measurements on four coupons. Fuel switches are represented by the vertical dotted lines. These data have been further consolidated and presented in a different format (Figures 3 and 4), in which the columns are arranged in order of increasing aromaticity of the first fuel in each fuel pair. These figures show just a single representative value for the mass % and volume % changes for each fuel switch. These data points are averages determined from the last measurement taken in each fuel on the four coupons. The equilibrium swell value for coupons in JP-5 after 43 days is marked on the bar charts as a reference point. More charts of this type can be found in Appendix E that include all fuel pairs tested.

It is important to note that the coupons with S-5 blends as first fuels and ECD-1 as the second fuel were mistakenly mixed up at switch number four. The mistake was realized on the second reading in the wrong first fuel, and the coupons were put back into the fuels in which they belonged. This didn’t seem to have any effects on the overall results. Both sets of coupons behaved as expected for their remaining time in the switch loading experiment. The effected values can be seen in Appendix Table E-1 and Table E-2.

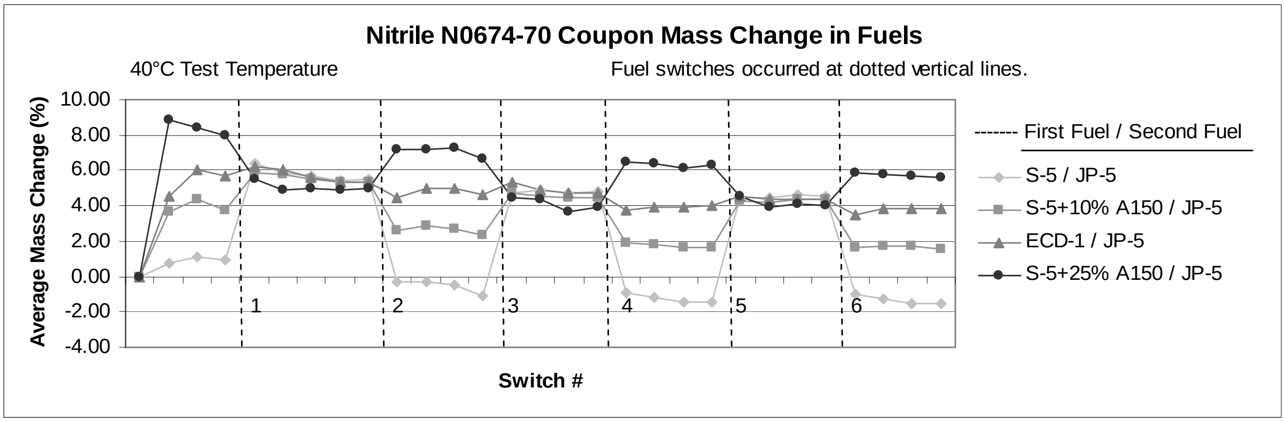

Figure 1. Avg. Mass Change (%) for Nitrile N0674-70 Coupon Switch-Loaded between Fuels

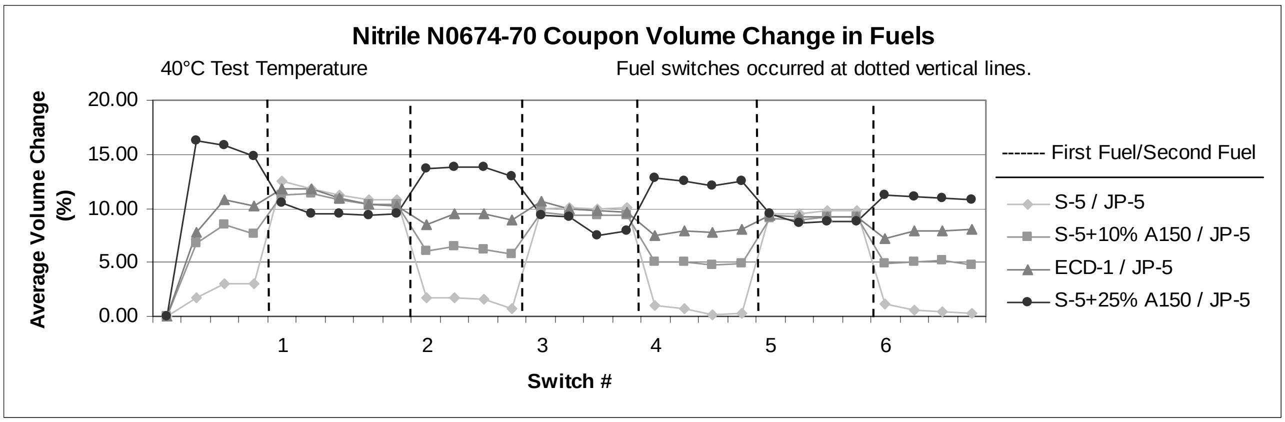

Figure 2. Avg. Volume Change (%) for Nitrile N0674-70 Coupon Switch-Loaded between Fuels

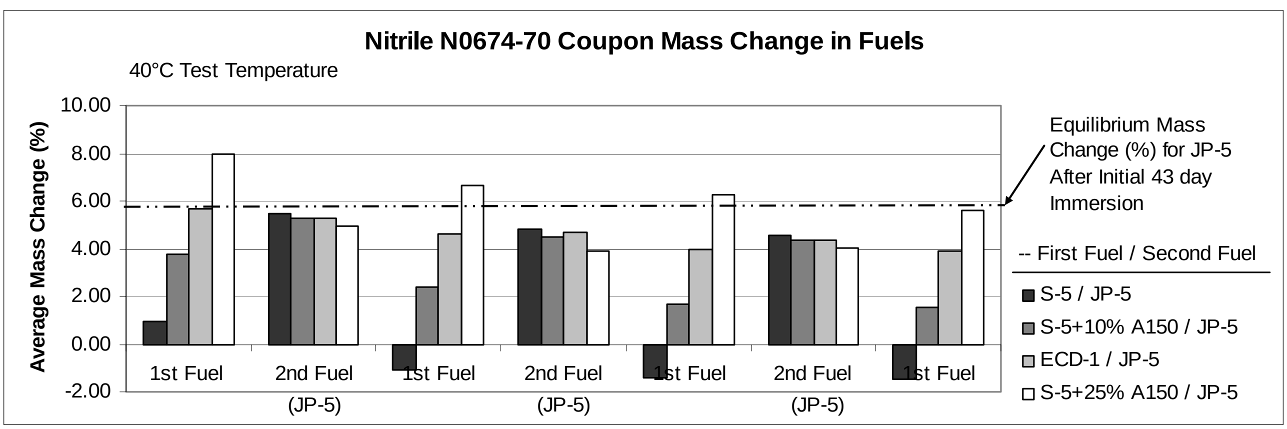

Figure 3. Mass Change (%) for Nitrile N0674-70 Coupon Switch-Loaded between Fuels

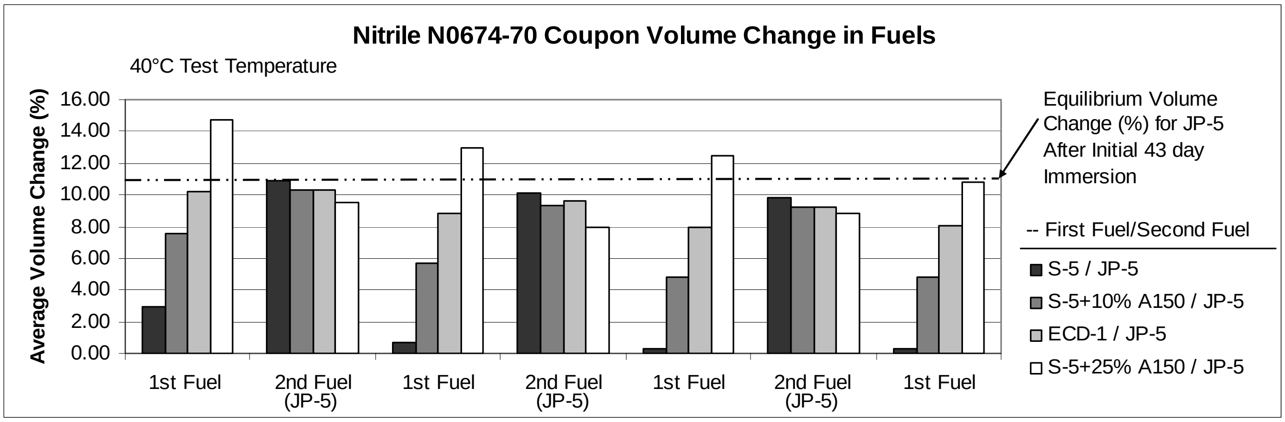

Figure 4. Volume Change (%) for Nitrile N0674-70 Coupon Switch-Loaded between Fuels

The O-ring data for mass and volume % changes followed similar trends as the coupon data, except the O-ring data showed smaller swings in swell. Analogous graphs for the O-ring for mass and volume can be found in Appendix E, along with graphs describing inner diameter and cross section diameter behavior during the switch-loading. Tables listing values averaged from the four samples in each fuel accompany each bar chart. Hardness data for the coupons can be found in appendix F.

V. DISCUSSION

Based on prior work, many elastomeric materials are expected to exhibit swell in the presence of aromatic hydrocarbons. [8-11, 13-14] The approach in this investigation was to understand changes in the swell as the nitrile elastomer was switched back and forth between current fuels containing aromatics and the S-5 fuel blends with surrogate aromatics. (Note: The effect switching the four coupons on the 230 mL sample composition was not evaluated in this effort.)

The nitrile studied in this evaluation responded to changing levels of aromatic content in the fuel as it was switched back and forth between the various fuel pairs. An example of this response is seen very clearly in Figures 1 and 2 for changes in nitrile N0674-70 mass and volume, respectively. For instance, the mass change of the nitrile coupon in the first fuel S-5 +25% A-150 is approximately +8.6%. After immersion in JP-5, the mass change declines significantly, to about 5.0%. Once the elastomer was switched back into the S-5 +25% A-150 fuel, it again increased in mass, although to a level slightly lower than that of the first immersion, that is, to about 7.0% rather than 8.6%. At the next fuel switch (back into the S-5 +25% A-150), once again the elastomer gained mass and reached a level near 6.3%. On the final switch into the S-5 +25% A-150, the elastomer only reached a 5.7% mass increase. This pattern of decreasing swell levels occurred for all fuels and is expected to continue, as evidenced by the O-ring mass data in Figure E-3, where the additional round of switch loading carried out for the O-rings can be seen. Each fuel produced a unique level of swell for the elastomer, depending on the aromatic content. The higher the level of aromatics in the fuel, the greater the elastomer swelled. The changes in % volume (Figure 2) show a similar pattern as fuel switches are made; the volume swings (“swings in swell”) between about 16.0% and 11.0% as switches are made from S-5 +25% A-150 to JP-5 and back again.

The swings in swell for the O-rings were much smaller than for the coupons. For coupon mass, percent change spanned from -1.0% in S-5, to over 8.0% in S-5+25%A150. The O-ring mass percent change only spanned from -0.5% in S-5 to about 2.3% in S-5+25%A150. Similarly, for volume, coupon percent change spanned from 0.5% in S-5 to over 16.0% in S-5+25%A150. O-ring volume percent change only spanned from -4.0% in S-5 to 12.5% in S-5+25%A150. Coupon vs. O-ring mass and volume data are provided in Figures 5 and 6, respectively. It would seem that, since the surface area to volume ratio for O-rings is nearly twice that of the coupon, the diffusivity of the fuel into the elastomer would be faster for the O-ring than the coupon. The data indicate that the coupon gained nearly three times as much mass in the same amount of time as the O-ring, while the specimen weight ratio is about 31:1 (coupon weight.: O-ring weight.). The fact that the coupons apparently had a much greater uptake of fuel may be partially due to the fact that the coupon test specimens had exposed cut edges as they were fabricated (cut) from nitrile sheet material, while the O-rings had no exposed cut edges as they were molded; the diffusion of fuel into the coupon could have been more readily accommodated through the coupon's exposed cut edges.

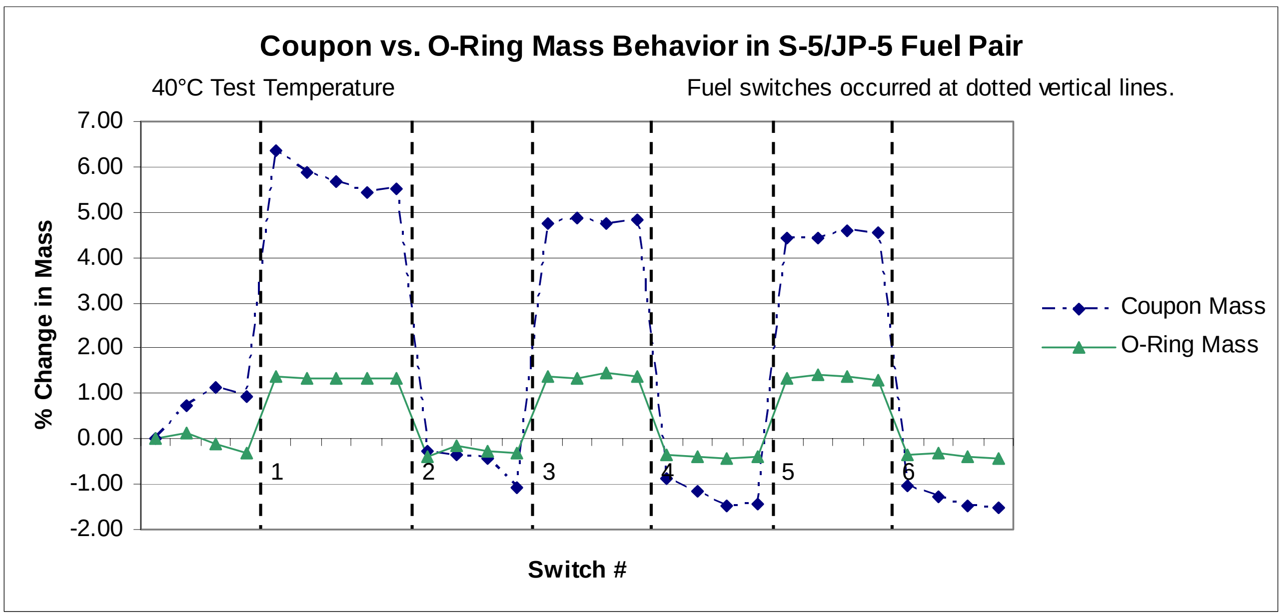

Figure 5. Comparison of Mass Percent Change Between Coupons and O-rings in S-5/JP-5

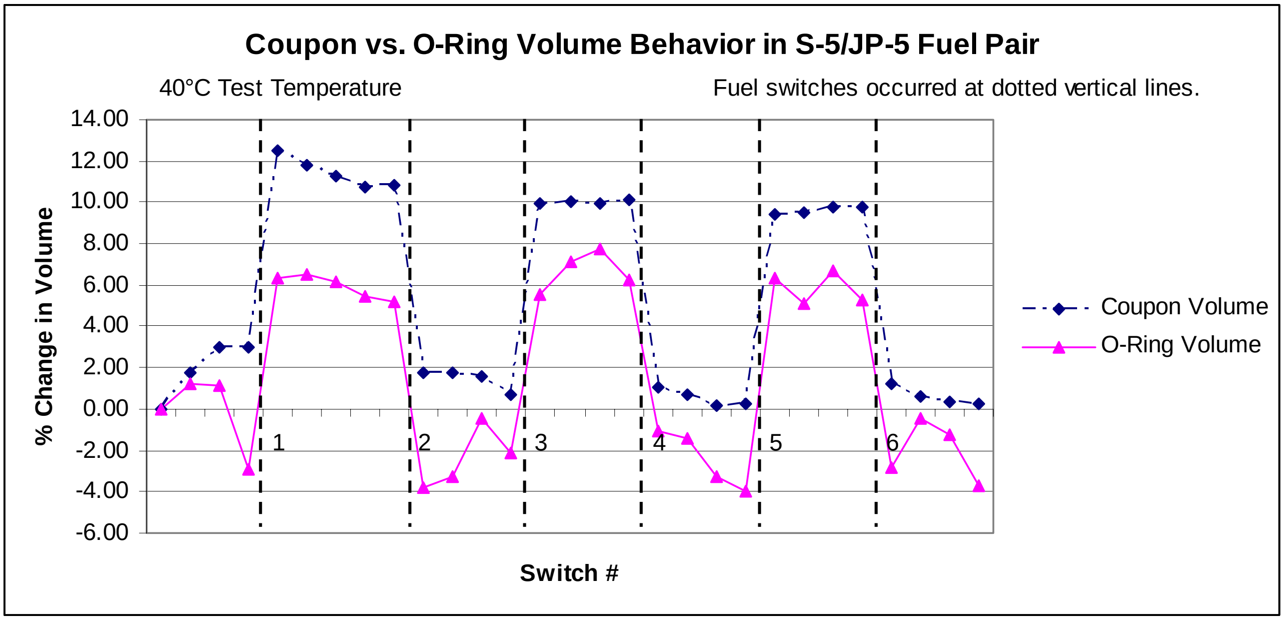

Figure 6. Comparison of Volume Percent Change Between Coupons and O-rings in S-5/JP-5

The O-rings when exposed to S-5, experienced negative mass and volume percent changes; that is, they lost mass and volume after exposure to S-5 as compared to their starting weights and volumes. This result can clearly be seen in Figures 1, 3, 5 and 6. Similarly, the coupons did experience a negative mass percent change, but never reached a negative volume percent change in S-5. At least the decreases in mass for both the O-rings and coupons suggests that the S-5 may be leaching something (such as fillers or plasticizers) out of the nitrile elastomer.

The hardness of the nitrile N0674-70 elastomer coupons followed a predictable behavior as seen in Figures F-1 and F-2 in Appendix F. After the coupons' first switch into petroleum fuels, and then the second switch back into the S-5 blends, the elastomers reached a hardness value slightly higher than their respective 43 day equilibrium values in the same fuel. Hardness values in the petroleum fuels were steady, while in the S-5 blends, the coupons exhibited a unique level of hardness relative to the amount of aromatic in the fuel. The higher the level of aromatics, the lower the hardness value. These results correlate well with trends observed for changes in mass and volume.

A summary of the results from this static switch-loading evaluation are shown in Figures 7 and 8 for Nitrile N0674-70 mass % and volume % changes, respectively. These figures show the delta volume percent change between switch "0" and switch "1" for all six fuel pairs evaluated, and compare coupon data to O-ring data. The data is presented with the largest difference in aromaticity within the fuel pair first, to smallest difference within the fuel pair last. This delta, between switch "0" and switch "1", is representative of the deltas found between subsequent switches as the response of the elastomer remained reasonably consistent as switches continued.

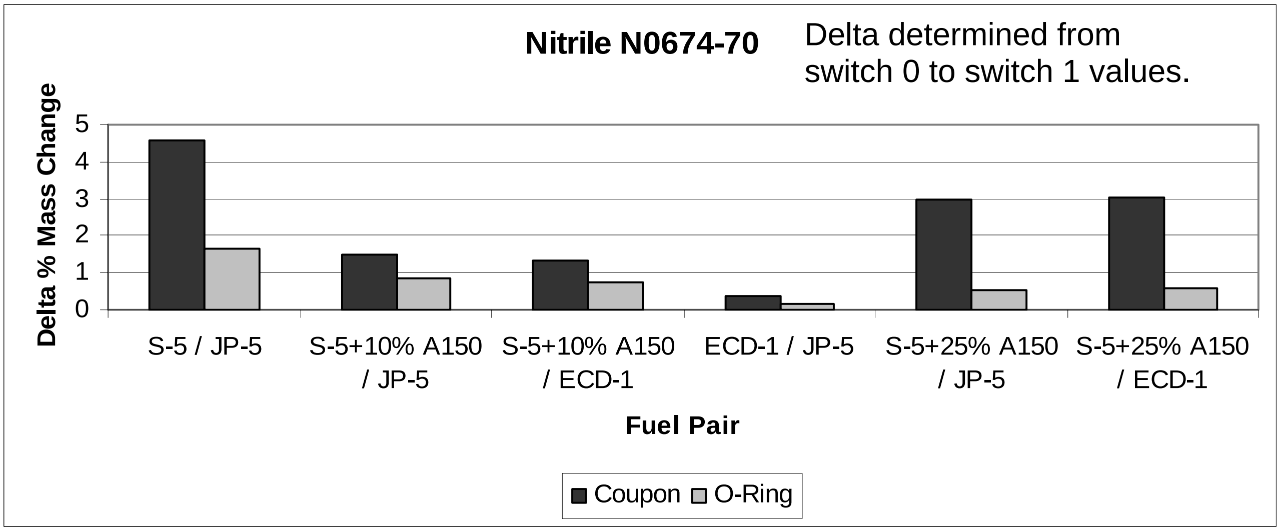

Figure 7. Delta % Mass Changes of Nitrile N0674-70 for All Fuels Switch-Loaded

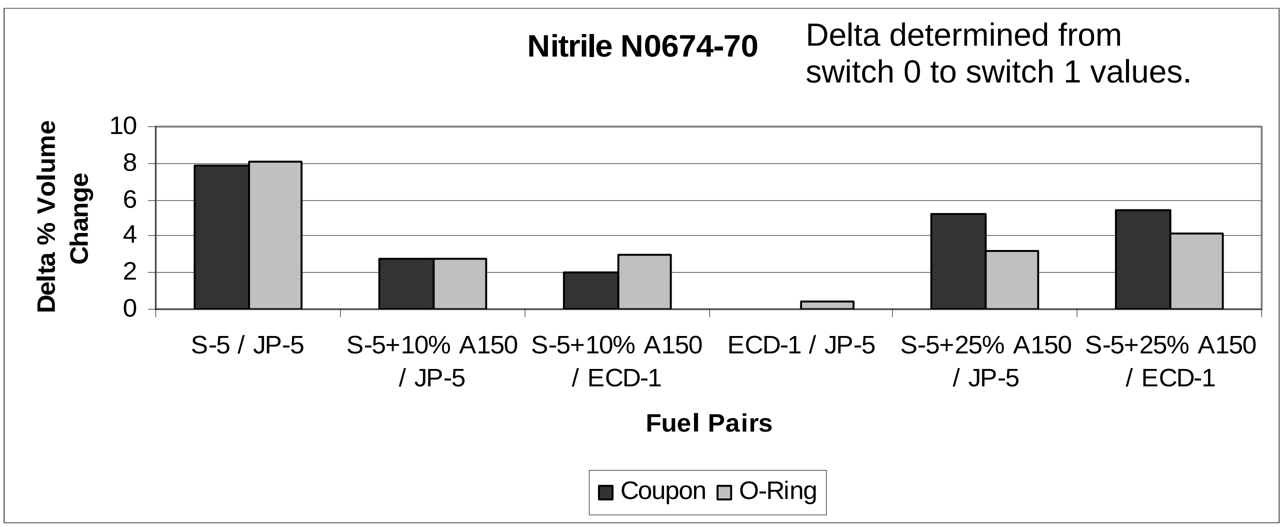

Figure 8. Delta % Volume Changes of Nitrile N0674-70 for All Fuels Switch-Loaded

The swings in swell are generally greater for the fuel pairs with the larger differences in aromatic content, while they are the least for the fuel pairs with the smaller differences in aromatic content. However, this is not entirely true. There is a slightly greater difference in aromaticities between the S-5+10%A150 and the petroleum fuels (JP-5: 18% and ECD-1: 19%) than between S-5+25%A150 and the petroleum fuels, yet S-5+25%A150 yielded significantly greater delta values. This indicates that the relationship between the difference in percent aromatics and effective swell is not linear.

VI. CONCLUSIONS & RECOMMENDATIONS

Results from this evaluation indicate that, for the nitrile elastomers evaluated, relatively large swings in swell occur with switches between fuels of varying levels of aromatic content and the synthetic

aviation turbine fuel containing no aromatics. These observations support the conclusion that impact on the nitrile elastomer when switch-loading (non-aromatic) synthetic and petroleum-derived fuel, is highly dependent on aromatic hydrocarbon type and concentration.

Highly aromatic fuels, such as JP-5 and S-5 + 25 % A150 resulted in O-ring volumetric swelling of more than 5 %. Fuels with low- or no-aromatic content experienced, in many cases, a volumetric shrinkage of about 1 %. This shrinkage, combined with an O-ring that has experienced compression set, such as one might find in the fuel system of an older vehicle, might result in a fuel leakage.

Bear in mind, however, that these dimensional changes were observed while the O-ring was in a free state, not one in which it was part of an assembly. Clearly, O-rings cannot swell or shrink more than the slight amount permitted by the surrounding non-elastomeric parts that would prevent further swell or shrinkage. As such, it is unknown as to whether the dimensional changes noted in this report are either good or bad. Rather, these results must be used in an academic fashion that compares the reaction of a Nitrile O-ring in one fuel versus another.

It is recommended that developing a performance requirement for a minimum swell of a specified reference nitrile elastomeric rubber may be more acceptable in a synthetic JP-8/JP-5 fuel specification as opposed to requiring a minimum aromatic content. This could help to ensure that the use of synthetic fuel would not adversely impact sealing capability.

The O-ring curing process, type and quantity of filler and plasticizers are noted variables between nitrile rubbers. Thus it is recommended that the nitrile elastomer O-rings in equipment be evaluated for comparative swell and compression set so that impact of low aromatic fuel on seal integrity can be addressed from a component standpoint prior to field demonstration.

It is recommended to study the results of compression set testing, comparing nitrile rubber, fluorocarbon, and fluorosilicone in both petroleum JP-5/JP-8 and S-5, both additized and un-additized. This is a test that the O-ring manufacturer should be enlisted to perform if it requires special fixtures.

It is recommended that the nitrile elastomeric materials and fuels used in this study be used in dynamic switch-loading test using a device designed and built by SwRI for evaluating shaft seals in dynamic applications. [15]

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14. Muzzell, P.; Stavinoha, L.; Villahermosa, L. “Elastomer Impact When Switch-Loading Synthetic and Petroleum Fuels,” TARDEC Report No. 14037, March 2004.

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APPENDICES

APPENDIX A

Properties of Fuels

Table A-1 • Properties of S-5 Fuel

Property, Units	Test Method	**Analysis by US ARMY** *S-5 X-03-001 Unadditized Batch 0001, Lot 0002*
Flash point, °C	ASTM D 56	62
Freezing point, °C:	ASTM D 5972	-50
Saybolt Color	ASTM D 156	+ 30
Total Sulfur, wt %	ASTM D 5185	<1 ppm
Distillation temperature, °C:	ASTM D 86	
Initial boiling point		183
10% recovered		194
20% recovered		201
50% recovered		219
90% recovered		254
Final boiling point (end point)		267
residue, % vol.		1.3
loss, %		0
Density at 15°C, kg/m^3	ASTM D 1298	0.764
Calculated Cetane Index	ASTM D 976 (ASTM D 4737)	69.5/67.3*(74.0)
Aromatics, % vol.	Internal method**	<1
Kinematic Viscosity, mm^2/s @ -20°C	ASTM D 445	6.0
Total Acid Number, mg KOH/g	ASTM D 664	0.0014
Total Water Content, %	ASTM D 6304	0.0019
Conductivity, pS/m	ASTM D 2624	1

Notes:
* Results shown for Equation 1/Equation 2 calculations
** Internal Method

APPENDIX B

Data Sheets for Elastomers Evaluated

Compound Data Sheet
O-ring Division United States

MATERIAL REPORT

REPORT NUMBER: KK2046
DATE: 2/06/90

TITLE: Evaluation of Parker Compound N0674-70 to ASTM D2000 2BG 720 EA 14 E014 E034.

PURPOSE: To document conformance to periodic test.

CONCLUSION: Parker Compound N0674-70 meets the requirements of ASTM D2000 2 BG 720 EA14 E014 E034.

Recommended Temperature Range: -30 to 250F

Recommended for: petroleum oils, water (up to 212F), Salt & Alkali solutions, weak acids

Not recommended for: aromatic fuels, strong acids, glycols, ozone, polar solvents

Parker O-ring Division
2360 Palumbo Drive
Lexington, Kentucky 40509
(859) 269-2351

REPORT DATA

Report Number: KK2046

BASIC PROPERTIES	2BG720 EA14 E014 E034	N0674-70 ATM D2000 RESULTS	PLATEN
Hardness, Shore A, pts.	70 ± 5	71	
Tensile Strength, psi. min.	2000	2546	
Elongation, % min.	250	331	
HEAT RESISTANCE 70 HRS. @ 212°F			
Hardness chg. pts.	±15	+6	
Tensile Strength chg, %	±30	+6.3	
Elongation chg, % max.	-50	-30.2	
COMPRESSION SET, 22 HRS. @ 212°F			
% of original deflection, max.	50	12.6	
EA14 WATER RESISTANCE, 70 HRS. @ 212°F			
Hardness chg. pts.	±10	+1	
Volume chg, % max.	±15	+1.1	
EO14 ASTM #1 OIL, 70 HRS. @ 212°F			
Hardness chg. pts.	-5 to +10	+3	
Tensile Strength chg, % max	-25	+5.5	
Elongation chg, % max	-45	-15.1	
Volume chg, %	-10 to +5	-2.3	
EO34 ASTM #3 OIL, 70 HRS. @ 212°F			
Hardness chg. pts.	-10 to +5	-7	
Tensile Strength chg, % max	-45	+2.9	
Elongation chg, % max	-45	-7.9	
Volume chg, %	0 to +25	+13.5	

APPENDIX C

Link to Datasheets for Aromatic Surrogates

http://www.exxonmobilchemical.com/Public_Products/Fluids/Aromatics_HeavyAromatics/Worldwide/Grades_and_DataSheets/Aro_HeavyAromatics_Solvesso_Grades_WW.asp

APPENDIX D

Characterizations of Surrogate Aromatics

Table D-1. Characterization of Aromatic-150 and Naphthalene-depleted Aromatic-150 Solvents

Major Individual Constituents of Aromatic-150 (A-150) and Naphthalene-depleted Aromatic-150 (NDA-150) Solvents

Based on Data Provided by DoE National Energy Technology Laboratory, GC-FID and GC-MS Methods

Compound	vol. % of solvent	
	A-150	***NDA-150***
naphthalene	12.0	0.0
tetramethylbenzenes	22.0	25.6
ethyl-dimethylbenzenes	25.0	39.1
methylpropylbenzenes	8.3	8.4
pentamethylbenzene	1.9	0.0
methyl-methylpropylbenzenes	3.4	0.0
diethylbenzene	0.0	1.9
trimethylbenzene	0.0	1.8
diethyl-methylbenzene	0.0	1.8
subtotal alkyl-substituted benzenes	***60.6***	***78.6***
dihydromethylindene	3.0	3.0
methylindan	3.0	3.0
indane	0.7	0.7
Total Major Constituents Identified	***79.3***	***85.3***

Notes:

(1) No alkyl-substituted naphthalenes were detected in either the A-150 or the NDA-150.

(2) Naphthalene was detected in NDA-150, but at less than 0.1% vol.

APPENDIX E

Switch-Loading Results for N0674-70 GP Nitrile Coupon and O-ring, Changes in Mass, Volume, Inner and Cross Sectional Diameter

Table E-1. Mass Change (%) for Nitrile N0674-70 Coupon Switch-Loaded between Fuels

Elastomer Coupons - Average Percent Change in Mass						
Time in Fuels	S-5 / JP-5	S-5+10% A150 (A) / JP-5	S-5+10% A150 (B) / ECD-1	ECD-1 / JP-5	S-5+25% A150 (A) / JP-5	S-5+25% A150 (B) / ECD-1
Fuel 1-0 days	0.00	0.00	0.00	0.00	0.00	0.00
3 days	0.72	3.62	3.61	4.54	8.86	8.84
9 days	1.12	4.37	4.06	6.01	8.45	8.50
43 days	0.94	3.78	3.52	5.67	7.94	7.85
Switch 1						
Fuel 2-Week1	6.36	5.83	4.70	6.18	5.49	5.43
Week2	5.86	5.78	4.85	6.02	4.87	4.60
Week3	5.67	5.51	4.94	5.60	4.96	4.76
Week4	5.44	5.29	4.82	5.35	4.90	4.75
Week5	5.50	5.29	4.87	5.30	4.96	4.83
Switch 2						
Fuel 1-Week1	-0.28	2.59	3.22	4.42	7.22	6.85
Week2	-0.34	2.85	3.21	4.97	7.19	6.69
Week3	-0.44	2.70	2.83	4.98	7.28	6.74
Week4	-1.06	2.38	2.28	4.62	6.68	6.67
Switch 3						
Fuel 2-Week1	4.75	4.69	3.86	5.30	4.46	3.61
Week2	4.86	4.54	4.25	4.89	4.40	3.85
Week3	4.75	4.46	4.26	4.73	3.63	4.64
Week4	4.83	4.48	4.33	4.68	3.92	4.45
Switch 4						
Fuel 1-Week1	-0.89	1.88	6.94	3.73	6.50	2.65
Week2	-1.16	1.82	6.70	3.97	6.35	2.62
Week3	-1.48	1.63	4.33	3.92	6.13	6.16
Week4	-1.43	1.67	1.92	3.99	6.29	6.29
Switch 5						
Fuel 2-Week1	4.41	4.24	3.31	4.51	4.51	3.48
Week2	4.41	4.18	3.62	4.38	3.97	3.75
Week3	4.60	4.40	3.92	4.39	4.11	4.13
Week4	4.55	4.33	3.85	4.33	4.05	3.92
Switch 6						
Fuel 1-Week1	-1.02	1.64	3.05	3.46	5.89	6.48
Week2	-1.29	1.70	2.86	3.83	5.76	6.36
Week3	-1.50	1.72	2.75	3.83	5.65	6.27
Week4	-1.50	1.57	2.71	3.88	5.60	6.27

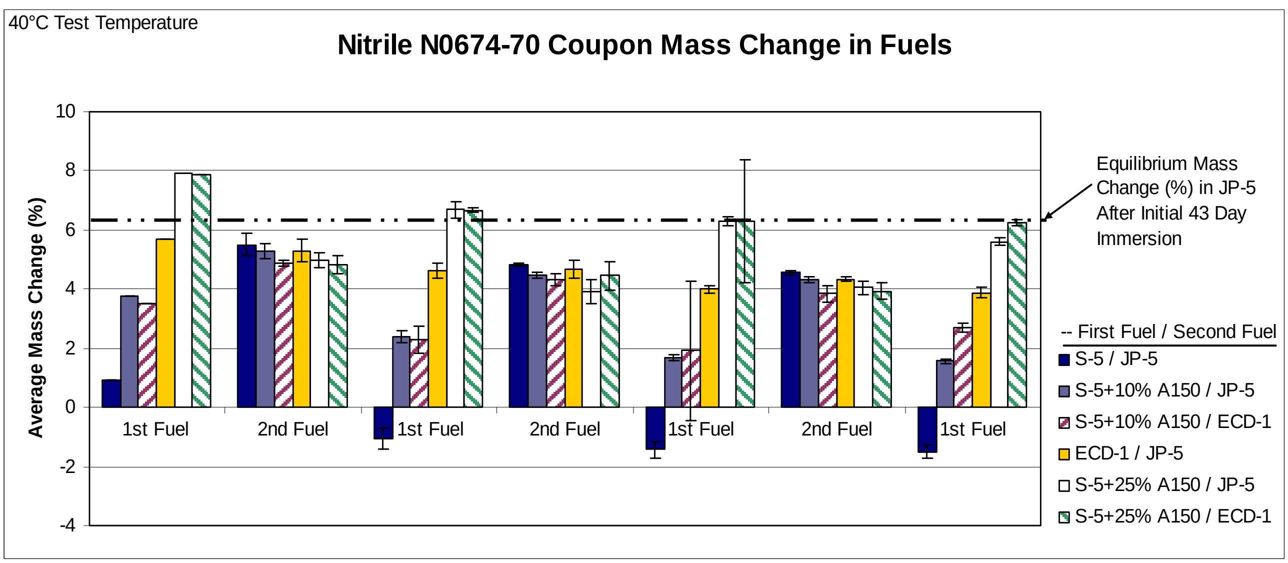

Figure E-1. Mass Change (%) for Nitrile N0674-70 Coupon Switch-Loaded between Fuels

Table E-2. Volume Change (%) for Nitrile N0674-70 Coupon Switch-Loaded between Fuels

Elastomer Coupons - Average Percent Change in Volume						
Time in Fuels	S-5 / JP-5	S-5+10% A150 (A) / JP-5	S-5+10% A150 (B) / ECD-1	ECD-1 / JP-5	S-5+25% A150 (A) / JP-5	S-5+25% A150 (B) / ECD-1
Fuel 1-0 days	0.00	0.00	0.00	0.00	0.00	0.00
3 days	1.79	6.73	6.72	7.77	16.24	16.20
9 days	3.00	8.51	7.93	10.73	15.77	15.83
43 days	2.98	7.57	7.17	10.22	14.75	14.59
Switch 1						
Fuel 2-Week1	12.49	11.24	8.71	11.82	10.56	10.51
Week2	11.79	11.40	9.22	11.79	9.47	8.93
Week3	11.23	10.75	9.19	10.92	9.49	9.07
Week4	10.77	10.32	9.03	10.40	9.40	9.08
Week5	10.86	10.30	9.24	10.28	9.50	9.20
Switch 2						
Fuel 1-Week1	1.79	5.99	7.13	8.47	13.73	13.20
Week2	1.78	6.48	7.17	9.48	13.77	13.09
Week3	1.57	6.20	6.50	9.45	13.86	13.09
Week4	0.67	5.71	5.59	8.87	13.00	12.95
Switch 3						
Fuel 2-Week1	9.91	9.61	7.67	10.67	9.32	7.33
Week2	10.08	9.36	8.38	9.89	9.22	7.74
Week3	9.94	9.29	8.42	9.71	7.48	9.65
Week4	10.10	9.34	8.57	9.63	7.97	9.34
Switch 4						
Fuel 1-Week1	1.08	5.06	13.45	7.47	12.78	6.35
Week2	0.68	5.05	13.09	7.95	12.55	6.37
Week3	0.19	4.73	9.07	7.79	12.15	12.16
Week4	0.28	4.82	5.18	7.99	12.46	12.41
Switch 5						
Fuel 2-Week1	9.44	9.01	6.91	9.33	9.49	7.31
Week2	9.51	8.95	7.48	9.25	8.68	7.74
Week3	9.77	9.20	7.91	9.17	8.79	8.33
Week4	9.78	9.26	7.88	9.19	8.83	8.05
Switch 6						
Fuel 1-Week1	1.20	4.93	7.61	7.26	11.27	12.84
Week2	0.61	5.01	7.31	7.84	11.01	12.62
Week3	0.39	5.17	7.22	7.95	10.93	12.53
Week4	0.30	4.82	7.12	8.01	10.84	12.49

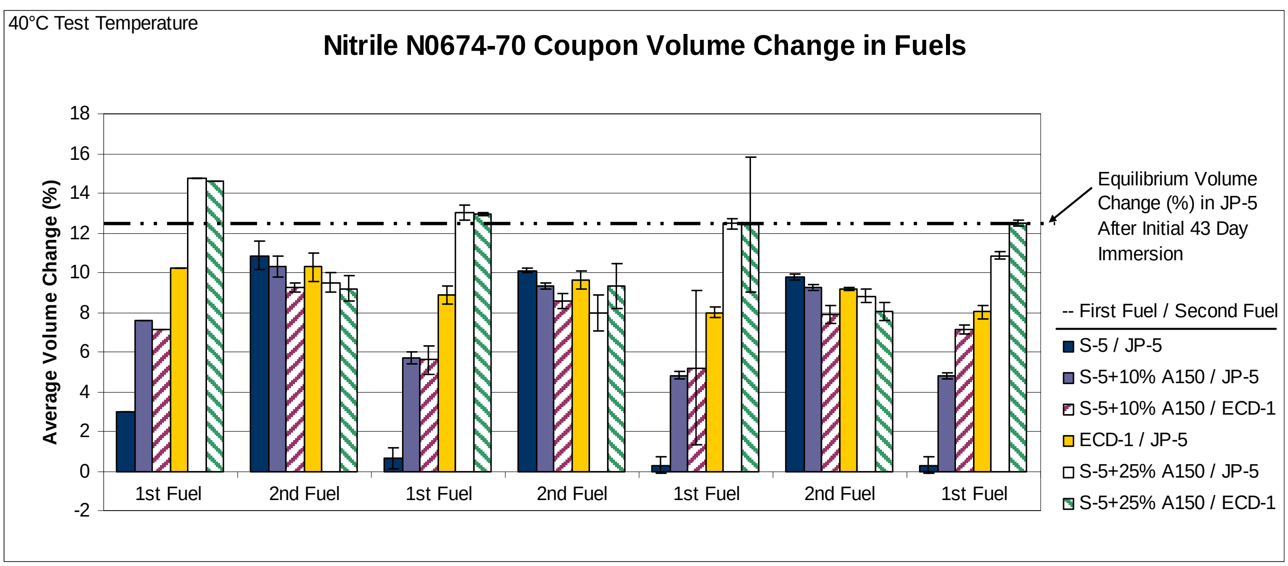

Figure E-2. Volume Change (%) for Nitrile N0674-70 Coupon Switch-Loaded between Fuels

Table E-3. Mass Change (%) for Nitrile N0674-70 O-Ring Switch-Loaded between Fuels

Elastomer O-Rings - Average Percent Change in Mass						
Time in Fuels	S-5 / JP-5	S-5+10% A150 (A) / JP-5	S-5+10% A150 (B) / ECD-1	ECD-1 / JP-5	S-5+25% A150 (A) / JP-5	S-5+25% A150 (B) / ECD-1
Fuel 1-0 days	0.00	0.00	0.00	0.00	0.00	0.00
3 days	0.11	1.02	1.08	1.53	2.25	2.31
9 days	-0.11	0.66	0.72	1.34	1.85	1.88
43 days	-0.30	0.49	0.58	1.26	1.79	1.84
Switch 1						
Fuel 2-Week1	1.38	1.34	1.28	1.43	1.26	1.13
Week2	1.33	1.31	1.29	1.38	1.22	1.18
Week3	1.33	1.35	1.39	1.44	1.31	1.24
Week4	1.32	1.32	1.32	1.38	1.22	1.20
Week5	1.34	1.36	1.34	1.43	1.24	1.23
Switch 2						
Fuel 1-Week1	-0.41	0.54	0.45	1.27	1.82	2.06
Week2	-0.16	0.49	0.44	1.13	1.94	1.84
Week3	-0.29	0.43	0.39	1.08	1.92	1.83
Week4	-0.33	0.48	0.46	1.20	1.97	1.94
Switch 3						
Fuel 2-Week1	1.39	1.32	1.13	1.31	1.39	1.18
Week2	1.33	1.20	1.14	1.18	1.26	1.16
Week3	1.47	1.32	1.22	1.34	1.41	1.23
Week4	1.36	1.25	1.18	1.24	1.30	1.15
Switch 4						
Fuel 1-Week1	-0.36	0.43	0.53	1.13	1.97	1.92
Week2	-0.38	0.46	0.55	1.12	2.04	2.02
Week3	-0.43	0.34	0.40	1.04	1.76	1.74
Week4	-0.38	0.38	0.42	1.12	1.88	1.85
Switch 5						
Fuel 2-Week1	1.35	1.20	1.12	1.24	1.24	1.09
Week2	1.43	1.25	1.13	1.30	1.28	1.14
Week3	1.38	1.27	1.23	1.31	1.32	1.29
Week4	1.30	1.17	1.24	1.20	1.24	1.30
Switch 6						
Fuel 1-Week1	-0.37	0.45	0.56	1.17	1.95	1.97
Week2	-0.33	0.44	0.48	1.18	1.92	1.93
Week3	-0.39	0.39	0.42	1.14	1.85	1.87
Week4	-0.43	0.36	0.41	1.11	1.82	1.83
Switch 7						
Fuel 2-Week1	1.26	1.13	0.98	1.19	1.16	1.07
Week2	1.33	1.18	1.09	1.27	1.24	1.16
Week3	1.29	1.17	1.02	1.20	1.18	1.12
Week4	1.31	1.26	1.07	1.30	1.18	1.14
Switch 8						
Fuel 1-Week1	-0.41	0.37	0.51	1.09	1.82	1.87
Week2	-0.43	0.35	0.42	1.12	1.81	1.83
Week3	-0.43	0.32	0.38	1.09	1.75	1.78
Week4	-0.48	0.30	0.32	1.07	1.69	1.72

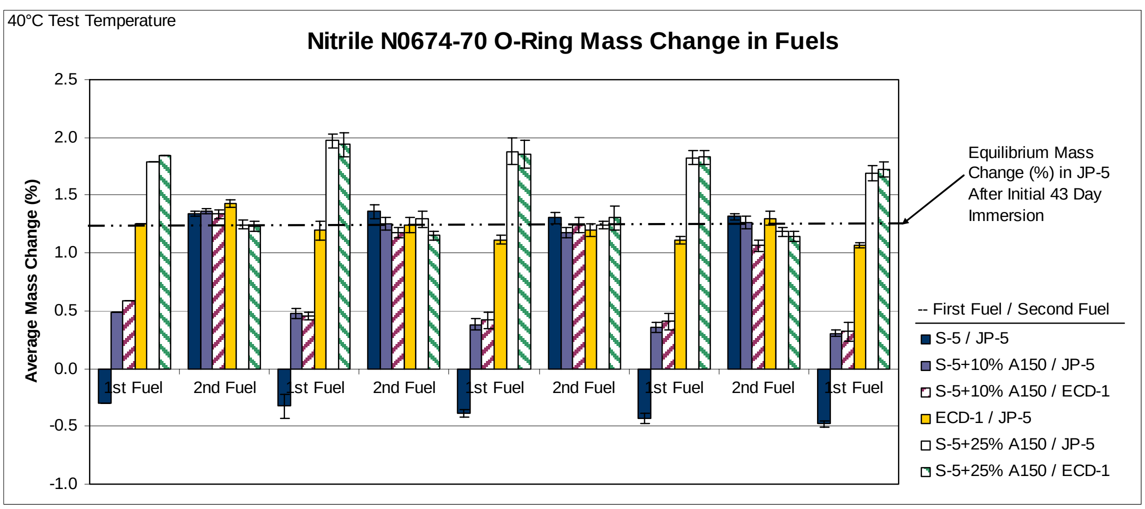

Figure E-3. Mass Change (%) for Nitrile N0674-70 O-Ring Switch-Loaded between Fuels

Table E-4. Volume Change (%) for Nitrile N0674-70 O-Ring Switch-Loaded between Fuels

Elastomer O-Rings - Average Percent Change in Volume						
Time in Fuels	S-5 / JP-5	S-5+10% A150 (A) / JP-5	S-5+10% A150 (B) / ECD-1	ECD-1 / JP-5	S-5+25% A150 (A) / JP-5	S-5+25% A150 (B) / ECD-1
Fuel 1-0 days	0.00	0.00	0.00	0.00	0.00	0.00
3 days	1.24	7.19	6.11	7.45	13.14	13.19
9 days	1.14	5.99	4.72	7.45	11.49	10.37
43 days	-2.92	3.56	2.19	5.61	9.16	9.57
Switch 1						
Fuel 2-Week1	6.30	8.56	6.55	6.47	8.32	6.78
Week2	6.53	8.03	5.96	6.76	7.37	6.11
Week3	6.13	7.40	6.33	6.34	8.12	6.41
Week4	5.41	7.17	6.38	5.73	7.45	5.86
Week5	5.19	6.28	5.19	5.19	6.00	5.41
Switch 2						
Fuel 1-Week1	-3.83	1.43	0.35	3.22	8.19	8.35
Week2	-3.31	0.98	-0.20	2.02	7.94	6.95
Week3	-0.47	3.34	2.68	4.84	10.81	10.02
Week4	-2.13	3.17	3.13	4.89	10.79	10.84
Switch 3						
Fuel 2-Week1	5.54	6.33	4.47	4.99	6.99	5.06
Week2	7.14	8.34	7.69	7.06	8.99	8.08
Week3	7.78	8.19	6.75	7.08	8.87	6.85
Week4	6.25	6.40	5.21	5.56	7.42	5.73
Switch 4						
Fuel 1-Week1	-1.09	3.64	3.30	5.09	11.16	10.24
Week2	-1.41	3.64	3.67	4.75	11.46	10.97
Week3	-3.26	1.30	1.34	3.03	8.94	8.25
Week4	-4.00	1.42	0.95	3.00	9.06	8.22
Switch 5						
Fuel 2-Week1	6.33	6.75	5.31	5.39	7.19	5.61
Week2	5.12	5.55	4.72	4.16	6.94	5.51
Week3	6.67	6.78	5.61	5.71	8.15	6.03
Week4	5.24	5.08	5.02	3.81	6.32	6.41
Switch 6						
Fuel 1-Week1	-2.79	1.60	2.44	3.76	8.92	9.22
Week2	-0.45	4.76	4.57	6.37	12.44	12.04
Week3	-1.21	3.34	2.21	5.31	10.19	9.77
Week4	-3.71	0.65	0.90	3.10	8.76	8.20
Switch 7						
Fuel 2-Week1	6.77	7.37	5.74	5.93	7.49	6.31
Week2	5.76	6.67	4.79	5.63	7.12	5.96
Week3	5.81	5.66	4.15	4.57	6.57	5.11
Week4	6.99	7.25	4.47	5.88	6.79	5.61
Switch 8						
Fuel 1-Week1	-2.27	2.39	2.41	4.48	10.31	9.82
Week2	-0.59	3.89	4.50	5.66	11.56	12.04
Week3	-0.86	4.21	3.68	6.10	11.79	10.87
Week4	-1.93	3.12	2.24	4.35	10.36	9.30

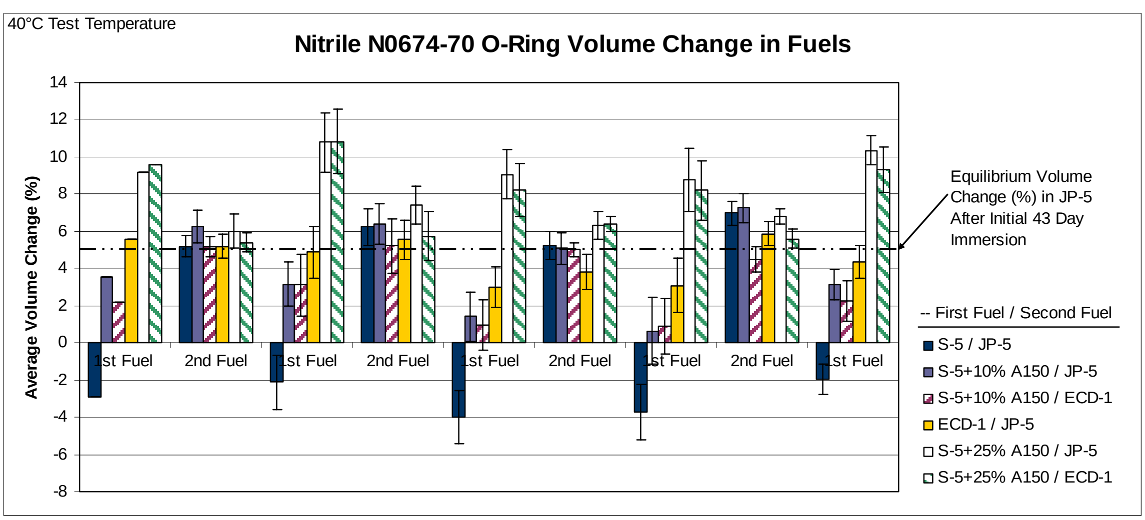

Figure E-4. Volume Change (%) for Nitrile N0674-70 O-Ring Switch-Loaded between Fuels

Table E-5. Inner Diameter Change (%) for Nitrile N0674-70 O-Ring Switch-Loaded between Fuels

Elastomer O-Rings - Average Percent Change in Inner Diameter						
Time in Fuels	S-5 / JP-5	S-5+10% A150 (A) / JP-5	S-5+10% A150 (B) / ECD-1	ECD-1 / JP-5	S-5+25% A150 (A) / JP-5	S-5+25% A150 (B) / ECD-1
Fuel 1-0 days	0.00	0.00	0.00	0.00	0.00	0.00
3 days	-1.37	-0.03	1.02	0.19	1.04	2.03
9 days	-0.24	1.56	1.77	1.69	3.29	3.05
43 days	-0.48	1.37	1.21	2.49	2.65	2.33
Switch 1						
Fuel 2-Week1	2.73	3.30	3.03	3.35	3.16	3.00
Week2	1.42	1.39	1.26	1.34	1.29	1.12
Week3	1.13	1.21	1.31	1.21	1.39	0.80
Week4	1.05	1.48	1.74	1.56	1.93	1.39
Week5	2.63	2.07	2.65	3.27	2.22	2.49
Switch 2						
Fuel 1-Week1	3.91	2.28	3.46	2.20	4.18	2.01
Week2	1.21	2.23	3.59	3.06	2.65	3.53
Week3	1.31	2.28	2.14	3.27	3.78	3.51
Week4	1.10	1.15	2.20	3.16	3.08	2.92
Switch 3						
Fuel 2-Week1	3.65	3.76	3.59	3.67	3.62	3.51
Week2	3.70	3.73	3.59	3.38	3.62	3.51
Week3	2.20	2.25	2.09	2.52	2.36	1.85
Week4	2.71	2.60	2.49	3.16	2.84	2.52
Switch 4						
Fuel 1-Week1	0.43	1.45	0.94	3.27	3.19	2.70
Week2	0.91	1.40	1.63	3.59	3.64	3.35
Week3	0.75	2.47	2.25	3.30	4.05	3.85
Week4	0.43	1.99	1.93	3.22	3.43	3.40
Switch 5						
Fuel 2-Week1	2.47	2.07	1.47	2.92	2.04	1.79
Week2	1.96	2.09	1.79	2.33	1.82	1.85
Week3	2.73	2.33	2.30	3.25	2.76	2.38
Week4	2.47	2.52	2.44	3.06	2.76	2.57
Switch 6						
Fuel 1-Week1	0.30	1.64	1.50	2.79	3.51	2.97
Week2	-0.48	1.34	1.26	2.79	3.62	2.73
Week3	-0.32	1.48	1.26	2.01	2.76	2.76
Week4	-0.16	1.66	1.31	2.71	3.03	2.84
Switch 7						
Fuel 2-Week1	2.57	2.74	2.46	3.41	2.73	2.62
Week2	2.52	2.55	2.30	2.76	2.46	2.30
Week3	2.12	2.12	2.36	2.49	2.44	2.33
Week4	2.41	2.15	2.38	2.07	2.44	2.25
Switch 8						
Fuel 1-Week1	-0.13	1.21	1.10	2.60	2.55	2.44
Week2	-0.21	0.86	0.75	2.28	2.33	2.33
Week3	-0.43	0.91	0.83	1.80	3.24	3.02
Week4	-0.38	1.07	0.94	2.87	2.87	2.81

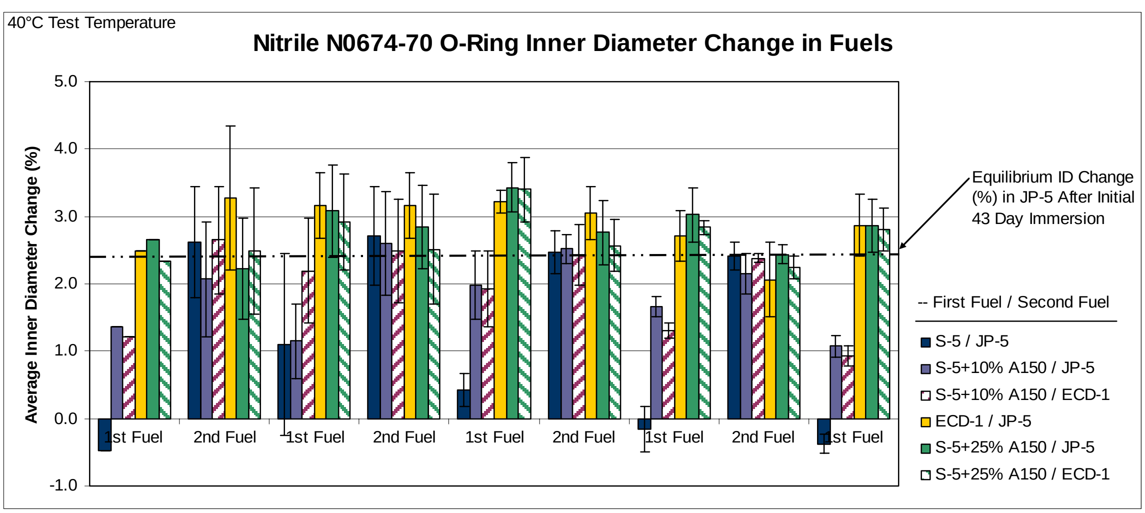

Figure E-5. Inner Diameter Change (%) for Nitrile N0674-70 O-Ring Switch-Loaded between Fuels

Table E-6. Cross-Section Diameter Change (%) for Nitrile N0674-70 O-Ring Switch-Loaded between Fuels

Elastomer O-Rings - Average Percent Change in Cross Section Diameter						
Time in Fuels	S-5 / JP-5	S-5+10% A150 (A) / JP-5	S-5+10% A150 (B) / ECD-1	ECD-1 / JP-5	S-5+25% A150 (A) / JP-5	S-5+25% A150 (B) / ECD-1
Fuel 1-0 days	0.00	0.00	0.00	0.00	0.00	0.00
3 days	-0.13	4.75	5.56	3.93	7.48	5.55
9 days	0.54	3.81	5.56	5.56	5.45	5.69
43 days	-1.49	1.50	2.57	1.36	4.35	4.60
Switch 1						
Fuel 2-Week1	-0.67	1.36	0.81	1.49	1.36	0.81
Week2	4.88	5.84	5.69	4.61	5.58	5.41
Week3	4.06	6.24	6.23	5.83	6.67	6.63
Week4	3.25	4.75	7.59	4.34	8.71	7.04
Week5	4.47	8.01	7.59	5.29	5.99	7.72
Switch 2						
Fuel 1-Week1	7.72	8.01	7.72	4.07	10.75	7.85
Week2	5.55	8.28	8.13	8.13	8.30	7.72
Week3	5.42	8.01	7.59	8.27	9.12	7.72
Week4	5.55	5.84	5.56	8.40	8.44	7.85
Switch 3						
Fuel 2-Week1	7.72	8.01	7.59	7.86	8.16	7.45
Week2	7.72	8.15	7.86	7.86	8.30	7.72
Week3	6.63	6.38	6.78	6.23	6.81	6.50
Week4	8.39	8.28	8.27	8.40	8.57	8.12
Switch 4						
Fuel 1-Week1	4.74	7.33	5.01	8.00	8.30	5.69
Week2	3.12	4.62	3.93	6.10	7.21	5.68
Week3	3.79	8.01	7.18	7.86	10.21	8.39
Week4	6.23	8.01	8.00	9.49	9.66	9.34
Switch 5						
Fuel 2-Week1	9.88	11.94	9.62	10.03	10.75	9.34
Week2	10.29	10.86	10.03	10.16	10.48	10.01
Week3	8.94	9.64	9.62	9.22	9.80	8.53
Week4	11.24	10.04	8.81	9.89	10.07	8.66
Switch 6						
Fuel 1-Week1	10.29	10.18	10.03	11.38	12.25	13.67
Week2	7.72	8.01	7.32	8.40	10.48	9.88
Week3	4.20	6.25	5.56	5.15	8.44	7.45
Week4	3.93	5.57	4.47	6.10	6.67	6.09
Switch 7						
Fuel 2-Week1	4.88	6.92	6.23	5.01	7.08	6.23
Week2	10.96	11.27	11.11	11.11	12.11	11.64
Week3	11.37	11.81	11.65	11.11	12.11	11.50
Week4	10.96	10.86	11.25	10.57	11.57	10.96
Switch 8						
Fuel 1-Week1	5.01	8.96	6.91	8.54	9.93	8.93
Week2	5.01	6.38	5.69	8.67	9.12	9.07
Week3	6.23	6.25	6.10	8.40	11.02	8.26
Week4	6.23	5.97	5.69	7.86	8.71	8.26

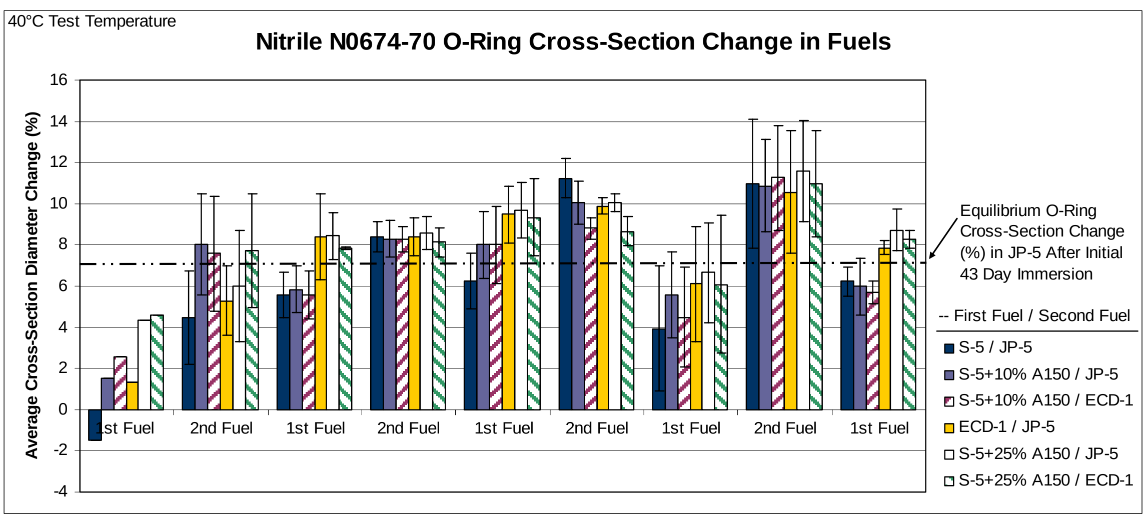

Figure E-6. Cross-Section Diameter Change (%) for Nitrile N0674-70 O-Ring Switch-Loaded between Fuels

APPENDIX F

Switch-Loading Results for Nitriles N0674-70 Coupon Changes in Hardness

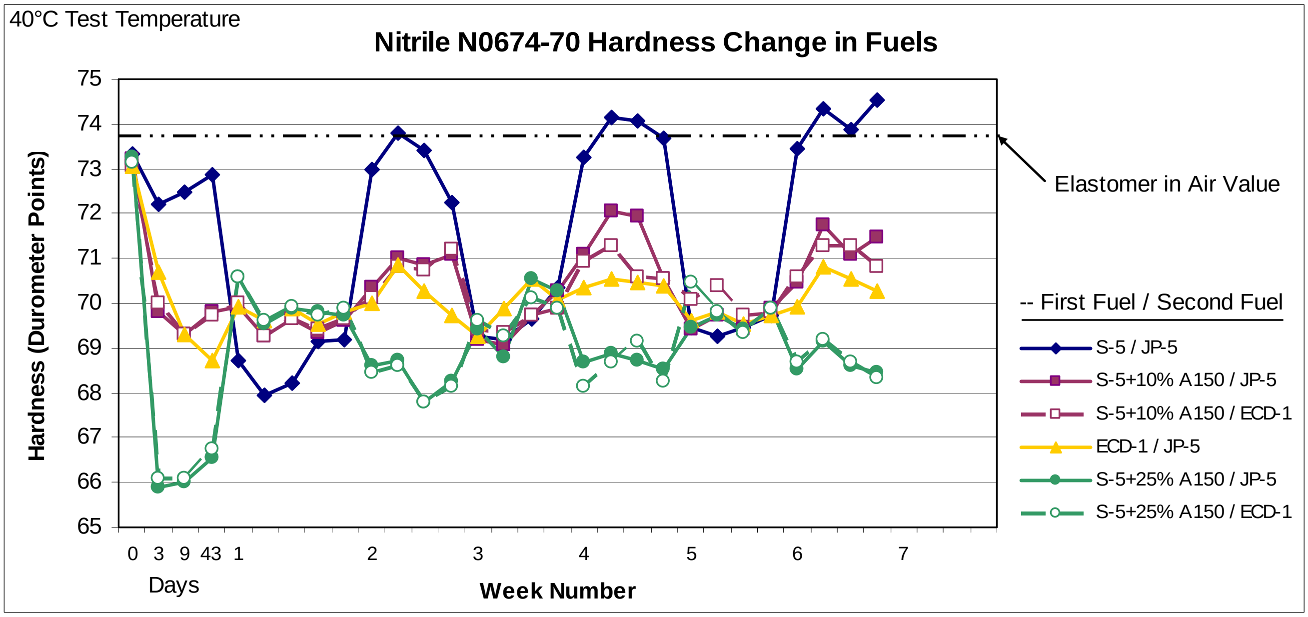

Figure F-1. Hardness for Nitrile N0674-70 Switch-Loaded in Various Fuels

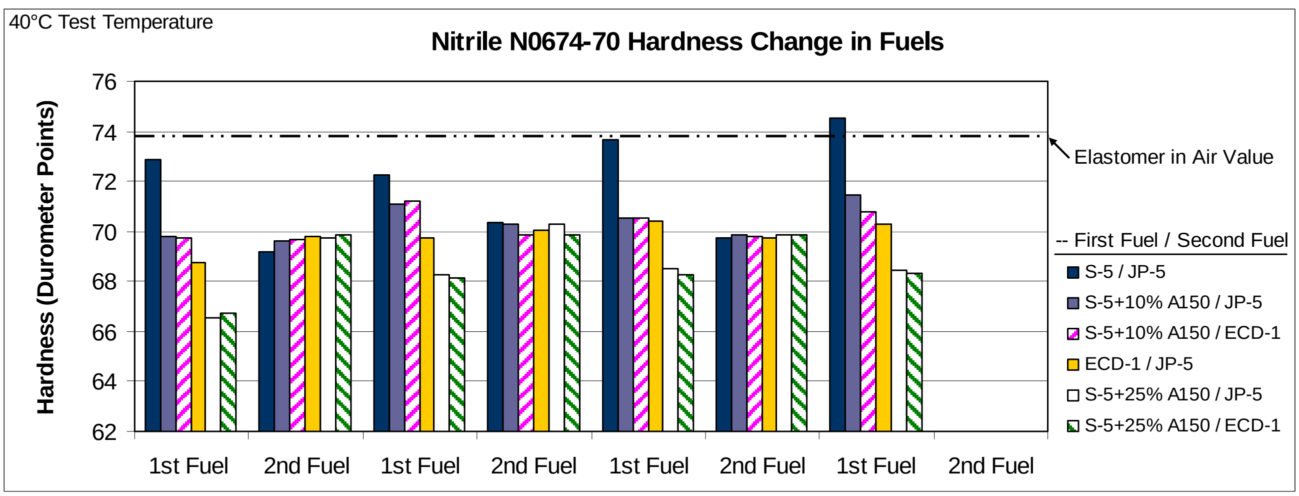

Figure F-2. Hardness for Nitrile N0674-70 Switch-Loaded in Various Fuels